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INTEGRATION OF INFRASOUND PROPAGATION MODELS AND NEAR-REAL-TIME ATMOSPHERIC CHARACTERIZATIONS

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This technical report has been reviewed and is approved for publication.

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14. ABSTRACT

The analysis tool kit InfraMAP (*Infra*sound *M*odeling of *A*tmospheric *P*ropagation) has been upgraded to offer new options for specifying the propagation environment. Near-real-time atmospheric updates, such as the output from numerical weather prediction models, supplement the baseline climatological characterization of temperature, wind and air composition. InfraMAP integrates advanced infrasound propagation models (ray-tracing, parabolic equation, normal mode) and environmental representations. It also incorporates algorithms for assessing propagation variability and for localizing infrasound sources based on both observations and model calculations. The component models have been integrated to allow for user-friendly model execution and data visualization.

Models can be applied to predict propagation characteristics necessary for estimation of travel times, bearings, and amplitudes from potential event locations worldwide. InfraMAP has been used to model long-range propagation of infrasound originating from the space shuttle, bolides and other sources. Model predictions of infrasound arrival times and azimuths resulting from use of various environmental characterizations are compared with observed data.

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Preface

Many people have assisted in the development of the multiple releases of InfraMAP during this and previous contracts, both through general discussions and by providing several of the base modeling capabilities contained in the InfraMAP software. In particular,

- Rod Whitaker and Doug ReVelle of Los Alamos National Laboratory (LANL) provided guidance on the modeling techniques and provided the WKB version of the normal mode code.
- Dean Clauter and Bob Blandford of the Air Force Technical Applications Center (AFTAC) provided guidance regarding the desired capabilities of the software and also provided historical data for validation purposes.
- Doug Drob of NRL's Upper Atmospheric Physics Branch provided advice, assistance and code for the HWM and MSISE atmospheric models, available from the NRL web site, and also the NRL-G2S atmospheric specifications. He also provided valuable insight regarding approaches to perturbation modeling of the propagation environment.
- Henry Bass of the National Center for Physical Acoustics, University of Mississippi, provided feedback regarding model selection and use.
- Joydeep Bhattacharyya of BBN (and formerly the Center for Monitoring Research) provided user feedback and supported infrasound analysis.
- Tom Georges of NOAA's Environmental Technology Laboratory provided the HARPA code, available from the NOAA/ETL ftp site, and a copy of the software documentation.

We would also like to acknowledge LANL and AFTAC for being beta test sites for the software.

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Section 1
Summary

InfraMAP, *Infrasonic Modeling of Atmospheric Propagation*, is a software tool kit that has been developed for use by researchers and analysts active in the study of infrasonic propagation and monitoring. The original development effort is summarized in a previous report [Gibson and Norris 2002a]. Certain enhancements that have been developed and integrated into new versions of the tool kit are described in a further report [Norris and Gibson, 2003]. This report addresses new capabilities to incorporate updates to the atmospheric characterizations.

Numerical modeling of infrasound propagation directly supports infrasound source location and phase identification. Predicting the details of infrasound propagation relies on characterization of the propagation medium, namely the global atmosphere from the ground to altitudes above 100 km, and the accuracy of propagation modeling depends on the fidelity of the atmospheric characterization. InfraMAP has been upgraded to offer new options for specifying the propagation environment. Near-real-time atmospheric updates, such as the output from numerical weather prediction models, supplement the baseline climatological characterization of temperature, wind and air composition.

InfraMAP integrates advanced infrasound propagation models (ray-tracing, parabolic equation, normal mode) and environmental representations. It also incorporates algorithms for assessing propagation variability and for localizing infrasound sources based on both observations and model calculations. New InfraMAP modules enable integration of propagation models with two near-real-time atmospheric characterizations. Output from the NRL-G2S (Naval Research Laboratory Ground to Space) specification can be imported and used to characterize the entire propagation environment. Alternatively, output from the Navy's synoptic model NOGAPS (Navy Operational Global Atmospheric Prediction System) can be imported into InfraMAP and merged with the baseline climatological models. These new capabilities extend the ability of infrasound researchers to investigate critical propagation phenomena, conduct sensitivity studies, and compare results of numerical modeling with observed signals.

Output from the propagation models was compared to measured data from historical events of interest in order to assess the value of improvements to the atmospheric specification. These comparisons have allowed identification of both the strengths of the software and areas where future efforts should be focused. InfraMAP has been used to model long-range propagation of infrasound originating from the space shuttle, explosions, bolides and other sources. Results of the analyses demonstrate the utility and flexibility of the software and also highlight important issues that must be addressed in order to achieve adequate propagation estimates and to estimate confidence bounds of infrasound source location.

Section 2
Introduction

2.1 Background.

Monitoring for nuclear explosions requires the ability to detect, localize and discriminate nuclear events. This monitoring is currently being implemented over a global scale through installation of 60 infrasonic stations in the International Monitoring System (IMS). Compared to other more mature monitoring technologies, infrasound has a greater number of unresolved issues, most of which involve the effects of atmospheric dynamics on propagation.

The standard method of infrasonic localization is based on taking measured back azimuths and arrival times and projecting them back to a source position. However, due to the temporal and spatial variability of the atmosphere, stable paths cannot be easily predicted for standard back-azimuth and time-of-arrival localization algorithms. It is generally anticipated that the ability to identify infrasound phases, and to include the appropriate travel-time and bearing refraction corrections for each arrival into localization procedures, would dramatically improve localization performance. The degree to which these capabilities can be developed and the specifics of how they should be used are major topics of research in the community.

The technical challenges involved in explosion monitoring using infrasound include the proper consideration of the effects of upper atmospheric dynamics on propagation. The large spatial and temporal variability of the atmospheric temperature and wind speed produces a very complicated infrasound propagation environment in which sound speed varies with time, location and altitude. Variability in sound speed and uncertainties inherent in characterizations of temperature and wind represent sources of uncertainty in source localization.

Under previous efforts for DTRA, BBN has taken steps toward addressing the needs within the infrasound monitoring community by developing the InfraMAP software tool kit. InfraMAP (Infrasonic Modeling of Atmospheric Propagation) is composed of research-grade infrasound propagation models (3-D ray tracing, parabolic equation and normal modes) and upper-atmospheric characterizations, integrated to allow for user-friendly model execution and data visualization. Temporal and spatial variability of the atmosphere is addressed by allowing range-dependent temperature and winds to be incorporated with the propagation models. InfraMAP was developed to enable the efficient application of advanced computational models, in support of the nuclear explosion monitoring research and development community. InfraMAP can be applied to predict travel times, bearings, and amplitudes from potential event locations worldwide. Such predictions can be used to identify infrasound phases and to define travel-time and bearing corrections, which can improve localization performance. Recent enhancements to the InfraMAP suite of computational tools enable analysis of propagation variability due to environmental effects, calculation of source location using measurements and model predictions, and prediction of network localization performance [Norris and Gibson, 2003].

2.2 Purpose.

Effective interpretation of infrasound signals in support of nuclear explosion monitoring is complicated by inherent spatial and temporal variability in the atmosphere. Effective phase identification and localization using infrasound stations relies on propagation model predictions for specific event scenarios. The dynamic nature of the environment and its impact on the predictions must be an integral component of a network performance evaluation. The ability to identify infrasound phases, and to include the appropriate travel-time and bearing corrections for each arrival into localization procedures, would dramatically improve localization performance.

The purpose of this effort was to develop new capabilities that allow infrasound analysts and researchers to model propagation through more realistic characterizations of the atmosphere, specifically, an enhanced InfraMAP software tool kit that enables higher-fidelity infrasound propagation modeling by making use of linkages to near-real-time atmospheric characterizations. The tool should provide environmental integration and execution capabilities for a baseline set of acoustic propagation models. Development of such an integrated set of models should allow for high fidelity propagation modeling by offering features such as range-dependent sound speed and winds. The ability to predict the critical infrasound propagation characteristics (travel time, azimuth, amplitude) that affect localization and network performance would therefore be enhanced. An extensive validation effort using a diverse set of observations and ground-truth will improve confidence in the modeling techniques and provide calibration in support of operational needs. Anticipated uses of the software include in-depth analysis of events and scenarios of particular monitoring interest, sensitivity analyses, and detailed infrasound localization and detection studies. The anticipated benefits to the nuclear explosion monitoring community are:

Improved propagation modeling capabilities – Improved characterizations of the dynamic atmosphere, including temporal and regional variability and the ability to incorporate near-real-time updates, coupled with InfraMAP's state-of-the-art propagation models. Ray tracing models will directly support event location. Normal mode, PE and ray tracing models will all support phase identification.

Improved infrasound localization – Better estimates of the infrasound propagation environment will improve predictions of azimuth deviation and travel time. The resulting bias predictions from InfraMAP can be used as input to localization algorithms.

Quantifying signals observed on the IMS network – Validation studies using InfraMAP models, applied to events of interest, will support future event identification and network calibration. Results from model studies and analyses of historical events such as rocket launches can be used as input to an infrasound database.

2.3 Scope.

The scope of this effort was to develop new atmospheric specification capabilities for the InfraMAP software that can be used to meet infrasound modeling requirements for nuclear explosion monitoring purposes. The specific goals for this effort were:

- Enhance the atmospheric characterization capabilities in InfraMAP.
- Develop an integrated software system capable of using infrasound propagation models with near-real-time sources of atmospheric information.
- Conduct model-to-measurement comparison studies to determine the effects of environmental variables on infrasound propagation, and validate that the modeling techniques are consistent with measured data.
- Integrate all new atmospheric capabilities and increased functionality into a new release of the InfraMAP software tool kit.
- Prepare a users' manual and documentation describing the tool kit.

Progress toward these goals is discussed in the remainder of the report.

2.4 Outline.

This section provides an introduction to the research effort. The remainder of the report summarizes the technical work that has been performed. Section 3 addresses methods, assumptions, and procedures in the model development process. Section 4 discusses the results of the effort by describing the new InfraMAP functionality and provides examples of its use. Studies are also summarized that have been performed using the software. The report ends with conclusions and recommendations.

Section 3
Methods, Assumptions and Procedures

This section describes the approach to the development and evaluation of the new capabilities of the InfraMAP software. The selection of environmental characterizations is addressed first, followed by discussion of the integration of atmospheric characterizations with propagation models. Finally, the software development methods are summarized.

3.1 Environmental Characterization.

In order to make adequate predictions of infrasound propagation, it is necessary to identify environmental characterizations that are suitable for defining the propagation environment. The existence of multiple atmospheric layers and large spatial and temporal variability in the atmospheric temperature and wind speed produces a very complicated infrasound propagation environment. Lower, middle and upper atmospheric temperature and wind data, required for predicting infrasound propagation paths, are currently available in a variety of formats at varying temporal and spatial resolutions, but no one data source contains all of the required environmental parameters at all locations and altitudes. Multiple atmospheric databases and models have been evaluated for use in InfraMAP, with consideration given to spatial and temporal resolution, coverage, and ease of implementation.

For an integrated infrasound modeling capability, both historical and "near-real-time" or updated environmental data are potentially useful for determining the best estimate of the environmental conditions affecting infrasound propagation. Consideration of the merits of individual data sources includes:

- Which sources of information have the most complete coverage (location, altitude and time)?
- Are these data at a resolution sufficient for accurate infrasound modeling?
- How should different data sources at different atmospheric layers be joined together?

Data sources generally fall into one of two categories: (1) raw data, such as those from individual measurements, and (2) assimilated data, which may consist of data on a standard grid or models that characterize a set of observed data. Examples of raw data sources include radiosondes, satellites and surface weather stations. None of the raw data sources provides the complete set of temperature and wind speed profile information needed for infrasound modeling.

The baseline for environmental characterization in InfraMAP consists of two empirical atmospheric models, developed at NASA and currently maintained by the Naval Research Laboratory. They are:

- the Horizontal Wind Model (HWM) [Hedin *et al.*, 1996] and
- the Extended Mass Spectrometer - Incoherent Scatter Radar (MSIS or MSISE) temperature and density model [Picone *et al.*, 1997].

HWM provides zonal and meridional wind components, and MSISE provides temperature, density and atmospheric composition. These environmental models have global coverage from the ground into the thermosphere and account for diurnal and annual effects. The HWM and MSISE models were chosen for use in InfraMAP due to their high fidelity over a wide range of altitudes and temporal scales, their global domain, and the relative ease of software integration. Global climatological models such as HWM and MSISE that are based solely on historical data do not capture fine-scale temporal and spatial atmospheric structure.

During this effort, an upgraded temperature and air composition model, NRLMSISE-00 [Picone et al., 1997] was incorporated in InfraMAP. NRLMSISE-00 is a recent upgrade from the earlier baseline temperature model, MSISE-90. Historical solar and geomagnetic data that are used as input to the empirical models have been obtained from the National Geophysical Data Center (NGDC). During this effort, an archive of solar flux and geomagnetic disturbance parameters (F10.7, F10.7A, and A_P) from NGDC has been integrated in InfraMAP, and appropriate daily values are automatically selected as defaults in a propagation run. In addition, a number of other enhancements have been introduced in InfraMAP to improve the fidelity of the environmental characterization. They include:

- Incorporation of variable molecular weight in sound velocity calculations;
- Incorporation of variable specific heat ratio in sound velocity calculations.

These new features are primarily intended to improve fidelity of the modeling of thermospheric infrasound at little or no computational cost.

Updated *in situ* environmental profiles, for example radiosonde data, can be used in conjunction with the InfraMAP propagation models, in a range independent mode, via a software option that allows user-defined profiles.

The InfraMAP enhancements made in this effort provide and utilize linkages to sources of measured and modeled atmospheric updates. Sources include:

- synoptic models of the atmosphere, such as those used in support of weather forecasting;
- updated observations of geomagnetic activity and solar flux, which affect upper atmospheric winds and temperatures.

Selected atmospheric characterizations are used in conjunction with empirical atmospheric models to define the infrasound propagation environment. Some of the issues for consideration in choosing an atmospheric characterization include:

- Are these data updated at a sufficient rate?
- How should data be accessed?
- Is there reliable global coverage 24 hours a day?

During this effort, new InfraMAP modules have been developed to incorporate output from physics-based synoptic models that assimilate observations from a number of sources. Range-dependent propagation modeling is now possible using these updated global atmospheric characterizations. Previously, updated atmospheric profiles could be used, but only in range-independent propagation modeling scenarios.

The near-real-time global atmospheric characterizations that have been integrated with infrasound models are:

- The Naval Research Laboratory Ground to Space (NRL-G2S) specification; and
- The Navy Operational Global Atmospheric Prediction System (NOGAPS).

Output from the NRL-G2S specification [Drob, 2003] can be used to characterize the entire propagation environment. NRL-G2S is a semi-empirical spectral model that fuses climatological models with output from operational numerical weather prediction models from NOAA, NASA and other sources. The G2S atmospheric characterizations from the surface to approximately 55 km utilize the output of multiple numerical weather prediction systems and other relevant global data sets. Above this region, upper atmospheric characterizations are based on the NRLMSISE-00 and HWM-93 climatologies. NRL-G2S employs spherical and vector spherical harmonics in the data assimilation process to produce a set of model coefficients for each day and time of interest. Coefficient sets can then be used to reconstruct fields of each atmospheric state variable as well as spatial derivatives.

An InfraMAP user can access NRL-G2S coefficient sets from a data repository, import the coefficients, and utilize the resulting specifications within InfraMAP to define a propagation environment. InfraMAP incorporates "client-side" routines [Drob, 2003] that perform inverse transforms necessary to determine vertical atmospheric profiles over the entire globe using the G2S coefficients. The NRL-G2S system is configured to produce coefficient sets autonomously every six hours, and also for special events of interest.

NOGAPS provides near-real-time global grids of temperature and wind, several times per day, over three spatial dimensions [Bayler and Lewit, 1992]. NOGAPS, originated by the Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC), is a numerical weather prediction system that utilizes not only profiles measured by radiosondes, but also an extensive data set of ship-based, land-based and satellite measurements. Output data from NOGAPS are readily available from the ground up to the 10 mb pressure surface (approx. 30-35 km). There is considerably more fine-scale structure in the NOGAPS characterization than in the climatology at altitudes below 35 km. However, because infrasound propagation modeling requires atmospheric information above the NOGAPS domain, climatological models remain an essential tool for estimating the environment, particularly at high altitudes.

Techniques have been developed within InfraMAP to merge NOGAPS grids at lower altitudes with climatological models at higher altitudes. InfraMAP modules import and decode NOGAPS grid files. A user then selects a subset of the global grid (i.e., a range of latitude and longitude cells) for use in a propagation scenario of interest. Within the region of interest, NOGAPS output is used in conjunction with the HWM and MSISE characterizations to define the propagation environment. A user specifies the thickness of the transition layer above NOGAPS. A cubic interpolation algorithm that matches the values and their derivatives at the boundaries is employed to join NOGAPS temperatures, zonal winds and meridional winds with the climatologies.

The global temperature and wind profiles from both the NRL-G2S and the NOGAPS characterizations can be viewed using InfraMAP's environmental menu. Furthermore, either near-real-time characterization can be used in range-dependent infrasound propagation modeling using ray-tracing or parabolic equation techniques or, alternatively, in range-independent propagation modeling using ray-tracing, parabolic equation or normal modes. This flexibility allows the direct comparison of the results of calculations using climatology or user-defined profiles with predictions using the near-real-time enhancements. It also allows the user to choose between computationally fast range-independent modeling and slower, higher-fidelity range-dependent modeling. Supplementing the baseline climatological models with available near-real-time updates is anticipated to yield improved infrasound predictions, particularly for propagation paths that dwell primarily in the lower and middle atmosphere, where updated data are more readily available.

3.2 Propagation Modeling.

Significant propagation model enhancements in InfraMAP were made in a recent effort [Norris and Gibson, 2003]. They fall into two categories: improvements in sophistication and efficiency, and improvements to support model-to-model and model-to-measurement comparisons.

During this effort, modifications to the internal interfaces between propagation models and environmental characterizations were required, but no fundamental changes to the propagation models were made.

In order to accommodate an environment defined by a gridded database such as NOGAPS, modifications have been made to InfraMAP's interface between propagation codes and environmental characterizations, particularly in order to allow range dependence. To propagate three-dimensional rays through gridded data, wind and temperature values and their spatial derivatives must be estimated at each point along a ray path. Because ray models are highly sensitive to sharp changes in sound speed, the estimation approach must avoid introducing gradient variability that is not inherent in the original data grid. A cubic interpolation algorithm that matches the values and their derivatives at the boundaries is employed to join NOGAPS temperatures, zonal winds and meridional winds with the climatologies. This approach results in smooth first derivatives and continuous second derivatives, which ensures that non-physical behavior is not introduced in the ray path predictions.

For range-dependent parabolic equation runs, computational efficiency has been significantly improved during this effort by gridding the range-dependent environments over a scale corresponding to their spatial resolution.

3.3 Variability and Network Performance.

Significant enhancements to InfraMAP for analyzing environmental variability and network performance were also made in a recent effort [Norris and Gibson, 2003].

As a result of this effort, the new capabilities in atmospheric characterization that have been introduced can be used in conjunction with InfraMAP's environmental variability and network performance tools, but no fundamental changes to the environmental variability and network performance models were made.

3.4 Software Implementation.

The InfraMAP software tool kit has been enhanced through the addition of new software modules that enable the near-real-time atmospheric capabilities. Capabilities were identified and prioritized for integration by using a benefit/cost tradeoff. The benefits included the ability to improve prediction fidelity and acceptance by the infrasound research community. The cost included the estimated integration effort and computational requirements. As integration of the modeling components progressed, the software was refined to simplify use and speed execution. The new graphical user interface (GUI) elements, including forms and data display formats, were designed and implemented using MATLAB®. A schematic block diagram of the software is shown in Figure 1.

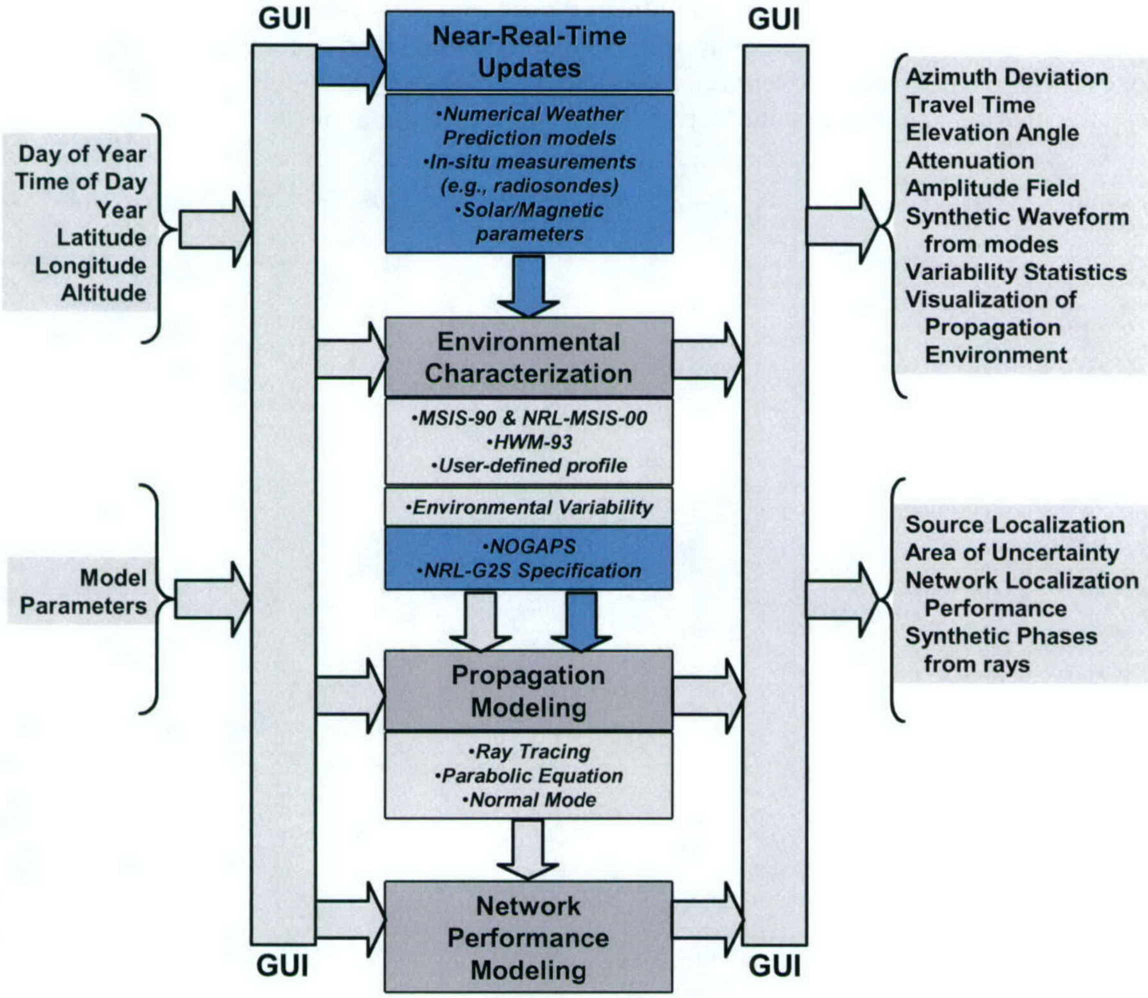

Figure 1. Schematic block diagram of InfraMAP functionality.

When using NRL-G2S with InfraMAP, coefficient sets are required to reconstruct fields of each atmospheric state variable as well as spatial derivatives. An InfraMAP user can use *ftp* (outside of InfraMAP) to access coefficient sets from an external data repository and import the coefficients and then utilize the resulting NRL-G2S specifications within InfraMAP to define a propagation environment.

If a new NOGAPS file is required, e.g., for a specific date or time, there are two ways to retrieve a new file. The first is a default mode in which retrieval is automated within InfraMAP. The second allows the user to retrieve NOGAPS files via *ftp* operations external to InfraMAP.

A prototype beta version of the software, including graphical user interfaces, was provided to selected users, and feedback received from the testers was used to prioritize further development activities. Recent development efforts have focused on improving calculation speed and efficiency of range-dependent propagation modeling.

The near-real-time update capabilities and other environmental enhancements have been integrated into the InfraMAP software tool kit, and an updated User's Manual has been developed. The most recent software release, InfraMAP 4.0, produced during this effort, provides the near-real-time atmospheric functionality described herein.

Section 4
Results and Discussion

This section details the results and accomplishments that have been made under this contract. First, the new capabilities of the software are summarized. Next, new environmental capabilities are described in more detail. Examples of analyses that have been conducted using the software are presented, including applications to events of special interest. The section concludes with a summary of reports and presentations that were completed during the effort.

4.1 Overview of New InfraMAP Functionality.

Several new features and capabilities have been added to the InfraMAP software tool kit during this effort. The following list provides a summary of new features added under this contract. Full details concerning InfraMAP operation and options can be found in the latest User's Guide [Norris and Gibson, 2004].

- *Upgraded Run Status Viewer* – Additional functionality and improved robustness.
- *Alternative Longitude Display* - Main map can be switched between two longitude display modes to avoid wrap-around of selected paths and regions.
- *New temperature model* - NRLMSISE-00 has been integrated for use in temperature and gas composition modeling, and is available for use with all propagation models.
- *New variable options for MSIS* - Molecular weight and specific heat ratio computed from MSIS can be displayed in the View Environment form.
- *Integrated archive of solar and geomagnetic parameters* – Improved capabilities by automated selection of appropriate parameters for selected day and year of interest.
- *Access to NOGAPS gridded output* – Links to ftp site for NOGAPS files. File conversion procedures. Capabilities for viewing environment. Cubic interpolation technique for merging with climatology. Integration with propagation models.
- *Use of NRL-G2S coefficient files* – Subdirectory for NRL-G2S files. Capabilities for viewing environment. Integration with propagation models. Upgrades to improve processing speed.
- *New molecular weight model* - A molecular weight model option has been added that allows for height and range dependent calculations based on MSIS air composition densities. Specific heat ratio is also calculated. Both of these variables are used to determine sound speed.
- *Improved PE efficiency* – For range-dependent runs, computational efficiency is significantly improved by gridding the range-dependent environments over a scale corresponding to their spatial resolution.

New menus, forms, display options and graphical user interfaces (GUIs) have been developed and integrated to support the new functionality. Examples of new forms are presented and explained in the InfraMAP User's Guide.

In conjunction with development of the alternative longitude display, useful when a great circle path or region of interest crosses the International Date Line, improvements were introduced to make propagation and display functions more robust around the poles and the Date Line. An example of ray tracing results is shown in Figure 2. A fan of ray paths to Chatham Island is shown. The symbol "BB" indicates "bottom bounce," where the ray reaches the surface.

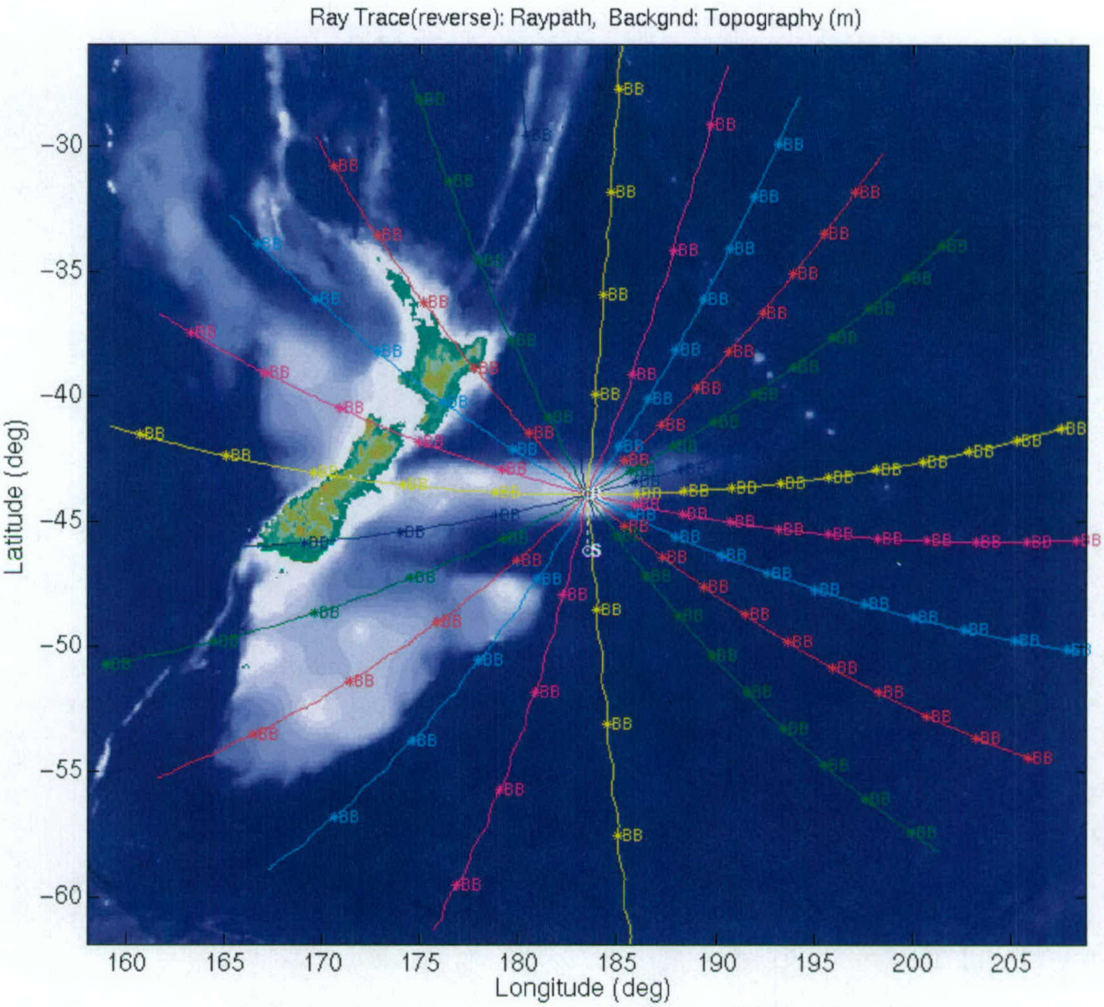

Figure 2. Example of ray tracing visualization across 180 degrees longitude.

4.2 Environmental Characterization.

The near-real-time global atmospheric characterizations that have been integrated with infrasound models are:

- The Navy Operational Global Atmospheric Prediction System (NOGAPS).
- The Naval Research Laboratory Ground to Space (NRL-G2S) specification.

4.2.1 Navy Operational Global Atmospheric Prediction System.

NOGAPS provides temperature and wind speed, several times per day, on a one-degree grid over 27 isobaric surfaces. Output data from NOGAPS are readily available from the ground up to the 10 mb pressure surface (approx. 30-35 km).

Figures 3 and 4 show examples of temperatures along a slice of the atmosphere between the South Pole and the North Pole, at a constant longitude, from NRLMSISE-00 and NOGAPS, respectively, for a particular day and time (2 July 1999). The large-scale temperature features are similar between the climatology and the near-real-time characterization, but the fine-scale structure is different. It can also be observed that the NOGAPS grid is non-uniform in altitude, due to the use of pressure surfaces rather than constant altitude surfaces. The upper boundary of the NOGAPS grid can be seen, varying between approximately 27 and 33 km in this case.

An additional example is presented in Figures 5 and 6, which show zonal winds over a region between the equator and the North Pole (in a Mercator-style projection), from HWM-93 and NOGAPS, respectively, for a particular day and time (29 September 2002). In the HWM figure, winds are shown at a constant altitude of 30 km. In the NOGAPS figure, winds are shown at the 10 mb constant pressure surface, which is at a slowly varying altitude of approximately 30 km throughout the region. The large-scale features are similar in the two figures, showing a shift in wind direction with increasing latitude. However, there is considerably more fine-scale structure in the NOGAPS characterization.

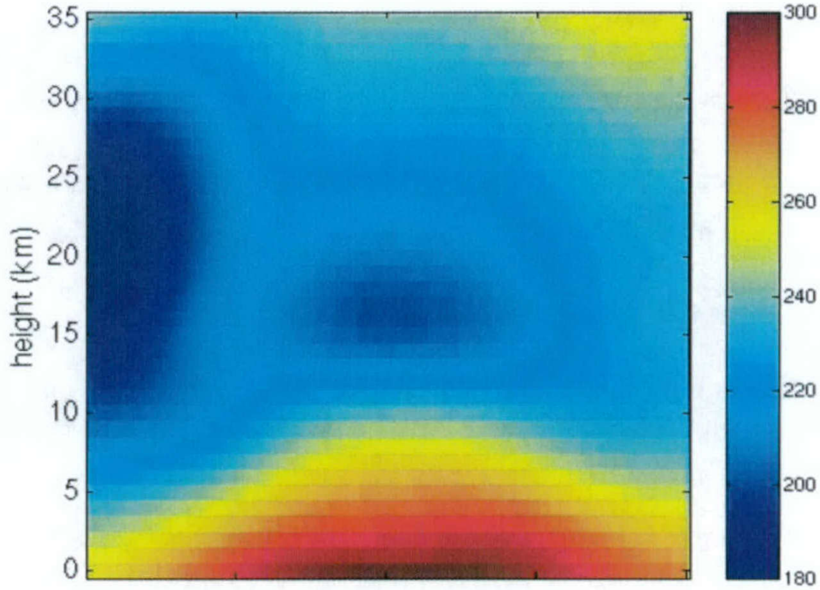

Figure 3. Temperatures (in degrees K) from NRLMSISE-00 climatology along a slice of the atmosphere at constant longitude of 60 degrees W, for Year 1999, Day 206, 0 UT.

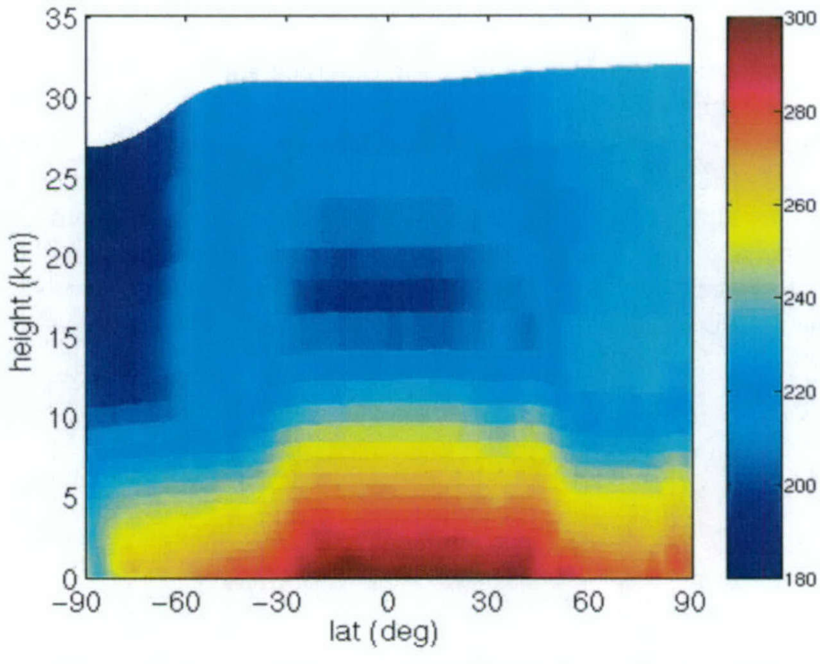

Figure 4. Temperatures (in degrees K) from NOGAPS along a slice of the atmosphere at constant longitude of 60 degrees W, for Year 1999, Day 206, 0 UT.

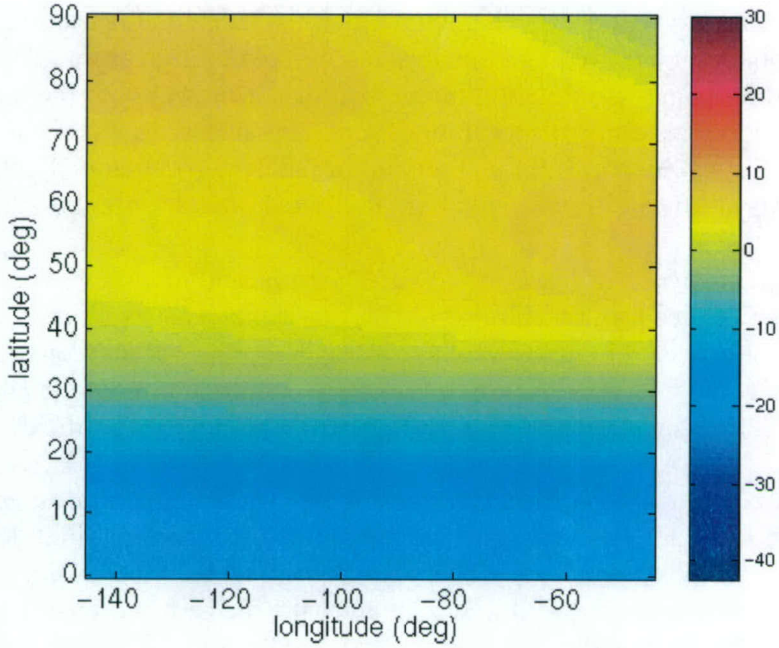

Figure 5. Zonal winds (in m/s) from HWM-93 climatology above a region of the northern hemisphere at constant altitude of 30 km, for Year 2002, Day 272, 0 UT.

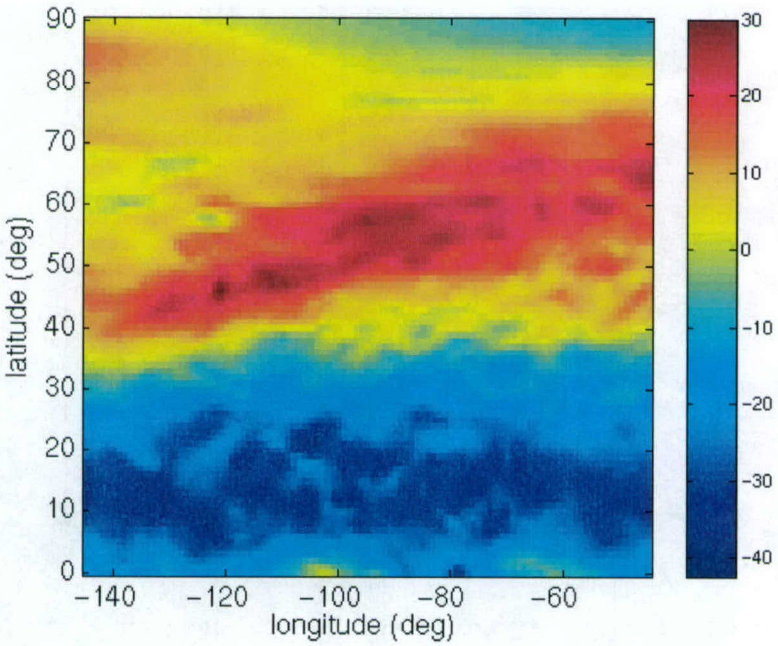

Figure 6. Zonal winds (in m/s) from NOGAPS above a region of the northern hemisphere at constant pressure surface of 10 mb, for Year 2002, Day 272, 0 UT.

NOGAPS is a promising environmental characterization for use with infrasound propagation models due to its global domain, frequent updates, and relatively high altitude coverage. However, infrasound propagation modeling requires information well into the thermosphere (approx. 120 km). Therefore, climatological models remain an essential tool for estimating the environment, particularly at high altitudes. Techniques have been developed within InfraMAP to merge NOGAPS grids at lower altitudes with climatological models at higher altitudes.

Links have been implemented to archives of NOGAPS grids, and modules have been developed to import and decode the files for use in InfraMAP. A user then selects a subset of the global grid (i.e., a range of latitude and longitude cells) for use in a propagation scenario of interest. Within the region of interest, NOGAPS output is used in conjunction with the HWM and MSISE characterizations to define the propagation environment. A user specifies the thickness of the transition layer above NOGAPS. A cubic interpolation algorithm that matches the values and their derivatives at the boundaries is employed to join NOGAPS temperatures, zonal winds and meridional winds with the climatologies. This approach results in smooth first derivatives and continuous second derivatives, which ensures that non-physical behavior is not introduced in the ray path predictions. Examples of resulting temperature profiles are shown in Figure 7. Four profiles are shown for locations at the corners of a specified region. The transition region in this case is 10 km in thickness.

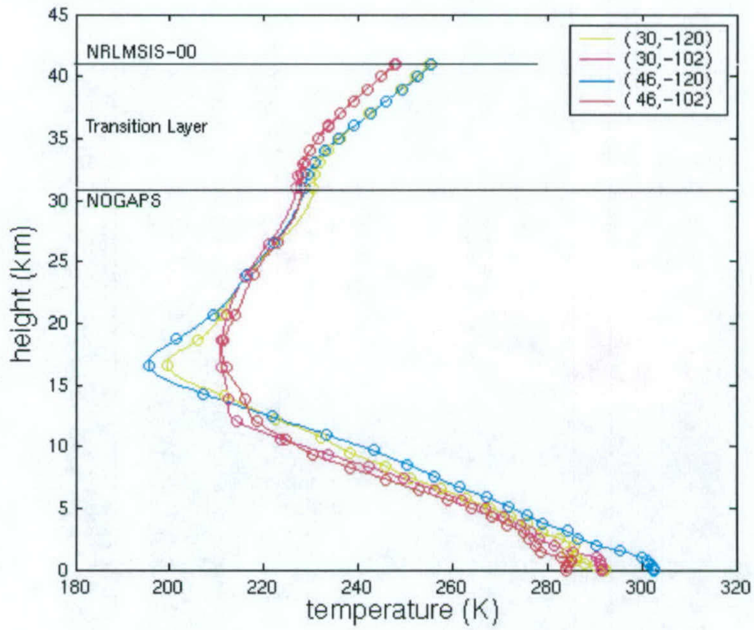

Figure 7. Temperature profiles (in degrees K) at four locations over North America. NOGAPS is used at lower altitudes and NRLMSISE-00 climatology is used at higher altitudes, with a transition region between. Year 2002, Day 272, 0 UT.

Examples of NOGAPS-derived profiles compared with climatology are presented in Figure 8. NOGAPS output, up to approximately 32 km altitude, and a 10 km transition layer defined within InfraMAP are shown in blue. MSIS and HWM profiles are shown in red. The hypothetical scenario is a 1000 km Eastward path to infrasound station IS41. Large-scale features are similar between the climatology and the near-real-time characterization, but the fine-scale features are different. Effective sound speed (static sound speed plus vector wind component) in the Eastward direction is also shown and reveals significantly different ducting characteristics between the two characterizations. Results of ray tracing through the two characterizations are also shown in the bottom panels of Figure 8. Two stratospheric eigenrays are found using the climatology. Complex ray paths involving stratospheric and tropospheric ducting are identified using NOGAPS. This example demonstrates that the use of numerical weather prediction models in propagation calculations can result in significantly different propagation predictions compared to climatology.

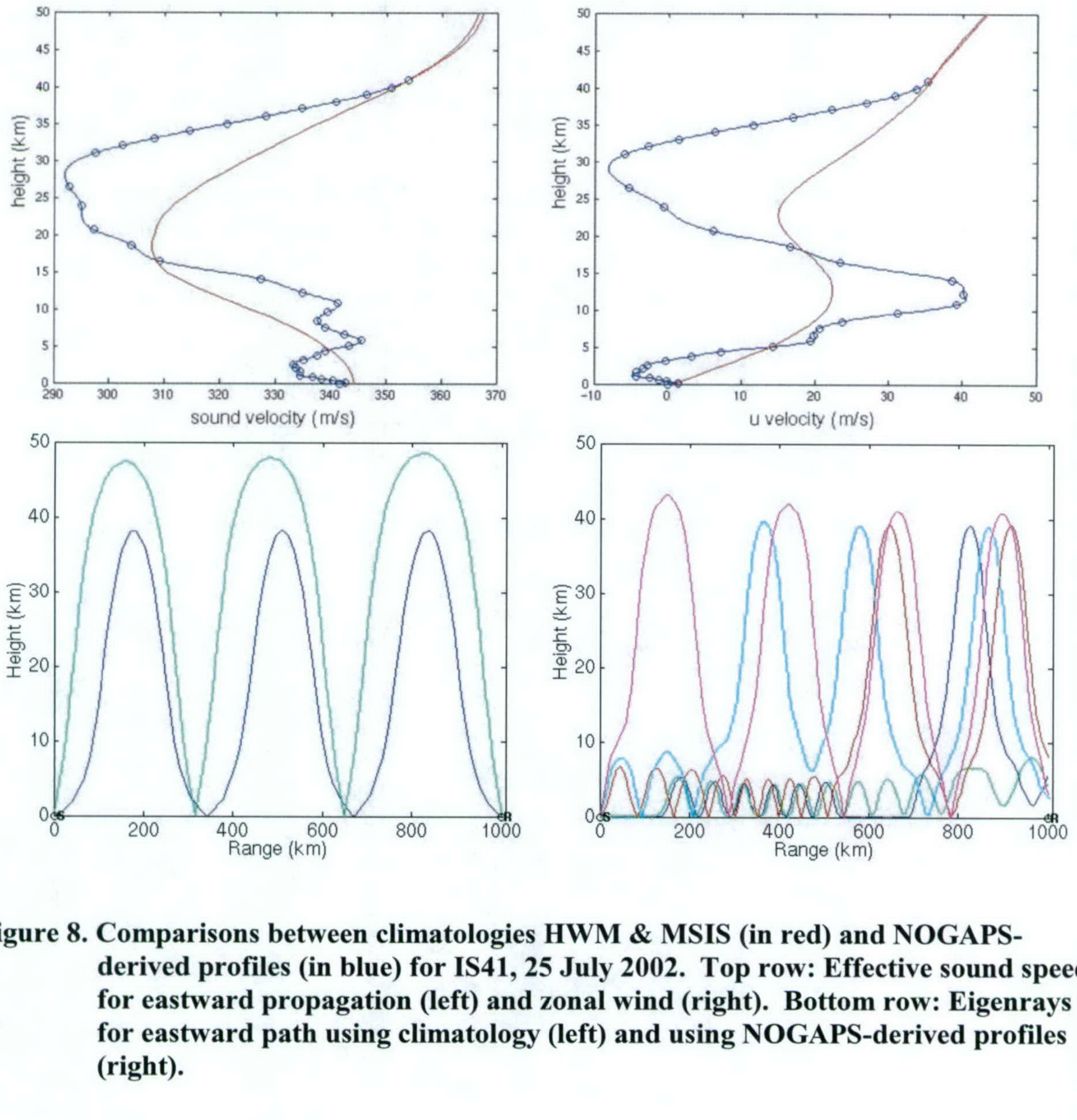

Figure 8. Comparisons between climatologies HWM & MSIS (in red) and NOGAPS-derived profiles (in blue) for IS41, 25 July 2002. Top row: Effective sound speed for eastward propagation (left) and zonal wind (right). Bottom row: Eigenrays for eastward path using climatology (left) and using NOGAPS-derived profiles (right).

4.2.2 Naval Research Laboratory Ground to Space Specification.

BBN and others have recently been investigating the applicability to infrasound of an additional near-real-time atmospheric characterization, the NRL Ground to Space (NRL-G2S) Global Atmospheric Specification System [Drob, 2003]. There is an increasing need to have accurate and timely specifications of the entire atmosphere for scientific research and engineering applications. Near-real-time data and detailed forecasts are now only routinely available in limited altitude regions (e.g., below 35 km). An atmospheric specification system that fuses state-of-the-art empirical models with operational numerical weather prediction specifications, the NRL-G2S semi-empirical spectral model produces global specifications and forecasts that are seamless and self-consistent from the ground to 750 km. InfraMAP allows the use of G2S specifications to define a range-dependent propagation environment suitable for a variety of infrasound propagation models. Use of G2S has been shown to be advantageous in previous infrasound calculation studies [Drob *et al.*, 2003, Le Pichon *et al.*, 2002, Garcés *et al.*, 1999].

Once G2S coefficients have been estimated, they are archived. From these coefficients, inverse transforms can be used to construct vertical profiles at specific locations. This formulation compresses the information and provides an efficient way to store, transmit, and reconstruct global volumes of environmental data as needed in client applications such as InfraMAP.

Figure 9 and Figure 10 show a comparison between G2S and climatology for a path corresponding to a train explosion event in Iran that was observed in Kazakhstan, as discussed in Section 4.3. Range-dependent effective sound speeds (0-120 km altitude) are shown over the propagation path. More fine-scale structure is present in the G2S specification. Significantly higher zonal wind velocities and effective sound speeds are predicted between approximately 30-50 km altitude using G2S. This difference is sufficient to define a stratospheric duct using G2S that is not predicted using climatology.

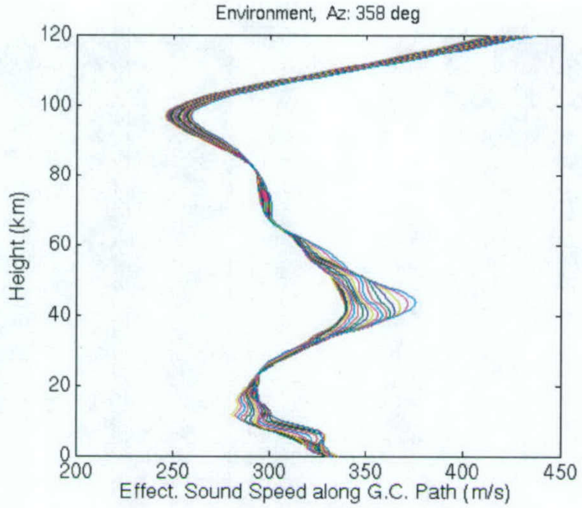

Figure 9. Effective sound speed profiles using NRL-G2S, calculated along a path from Neyshabur, Iran to infrasound station I31KZ, for 18-Feb-2004, 6:00 UT.

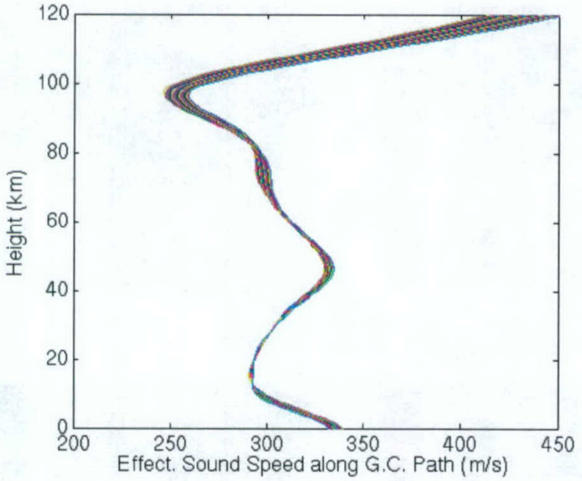

Figure 10. Effective sound speed profiles using climatology, calculated along a path from Neyshabur, Iran to infrasound station I31KZ, for 18-Feb-2004, 6:00 UT.

Results of propagation through these environments are discussed in Section 4.3.

Figure 11 shows an additional comparison between G2S, climatology and numerical weather prediction; in this case, NOGAPS-derived profiles generated using InfraMAP. Zonal and meridional winds (0-50 km altitude) are shown over a path from Cape Kennedy, FL to infrasound station I10CA, Lac du Bonnet, Manitoba, for 14-June-2003, 12:00 UT. Coarse features of zonal wind are similar in all three characterizations. Similar structure is shown in both the NOGAPS and G2S characterizations below approximately 30 km, but fine-scale details are slightly different. Some numerical "ringing" artifacts can be seen in the NOGAPS-derived profiles between 30 and 40 km, particularly for meridional wind; this feature may be due to the interpolation procedure in the InfraMAP transition zone.

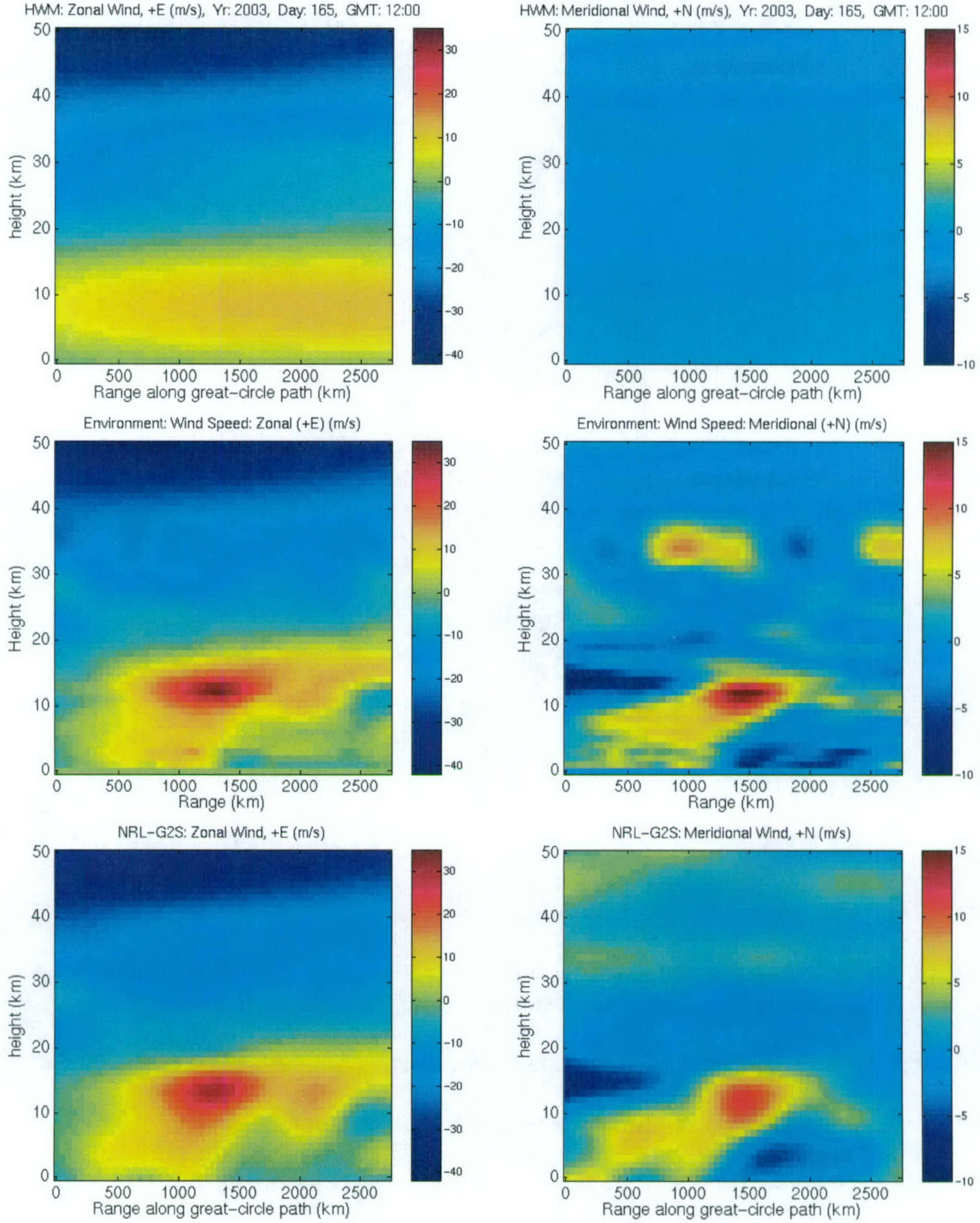

Figure 11. Comparisons between HWM climatology (Top row), profiles using NOGAPS, HWM and a transition zone (Middle row), and NRL-G2S (Bottom row). The Left column shows Zonal Winds; the Right column shows Meridional winds. Profiles are calculated along a path from Cape Kennedy, FL to infrasound station I10CA, Lac du Bonnet, Manitoba, for 14-June-2003, 12:00 UT.

4.2.3 Other Enhancements to Environmental Characterizations.

In addition to the incorporation of NRLMSISE-00, NOGAPS and NRL-G2S specifications, a number of other enhancements have been introduced in InfraMAP to improve the fidelity of the environmental characterization. They include:

- Integrated archive of solar and geomagnetic parameters;
- Incorporation of variable molecular weight in sound velocity calculations;
- Incorporation of variable specific heat ratio in sound velocity calculations.

These are primarily intended to improve characterization of the thermosphere.

Solar flux and geomagnetic disturbances from solar activity influence the modeled atmospheric temperature and winds above 100 km. The variables F10.7, F10.7A, and A_P are used as input to the HWM and MSISE models, and entry of values for these parameters allows their effects to be modeled in InfraMAP.

- A_P is the planetary equivalent amplitude of daily geomagnetic disturbance,
- F10.7 is the daily solar radio flux at 10.7 cm wavelength, and
- F10.7A is the 81 day average of F10.7 values, centered on the day of interest.

Daily values of the parameter A_P for the year 2001 are shown in Figure 12. Temperatures from MSISE, calculated for a range of thermospheric altitudes above the North Pole, are shown in Figure 13 for a representative range of A_P values.

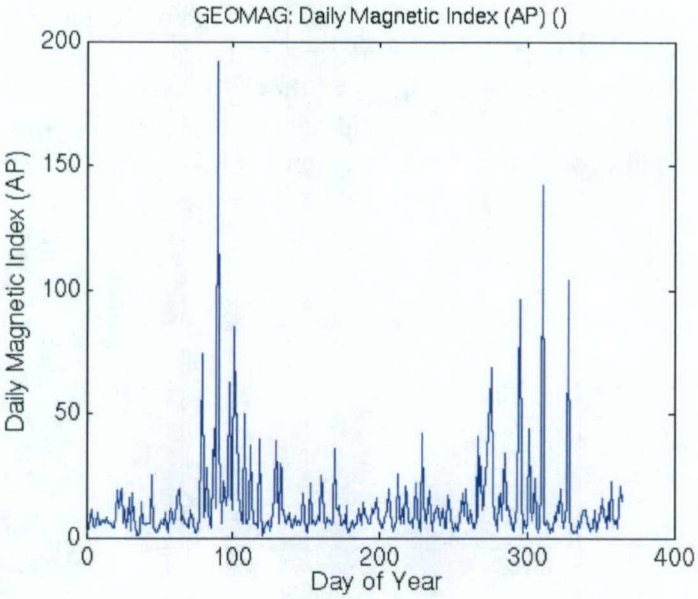

Figure 12. Daily values of geomagnetic disturbance parameter A_P for year 2001.

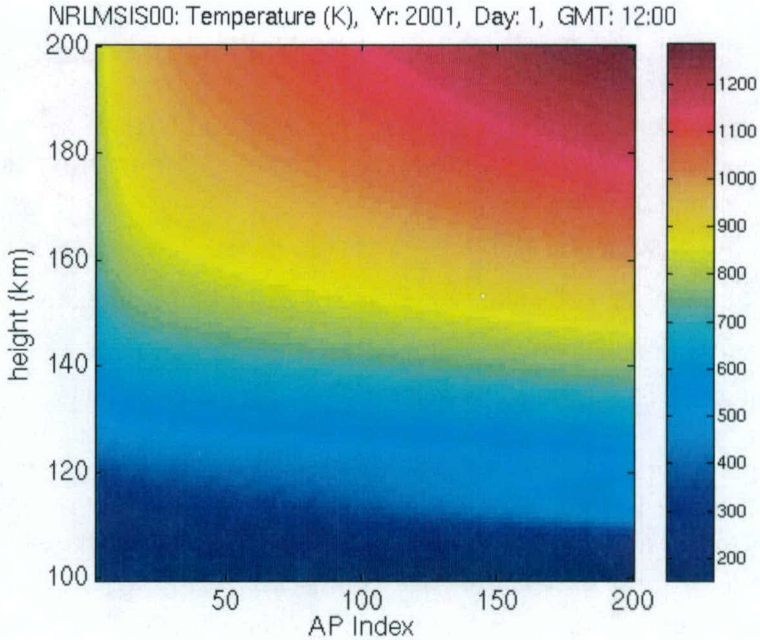

Figure 13. Thermospheric temperatures above the North Pole for a range of A_P, using NRLMSISE-00.

The values of the average molecular weight and the specific heat ratio (the ratio of heat capacity at constant pressure to heat capacity at constant volume), both of which depend on air composition, have effects on calculations of sound velocity and acoustic absorption. The determination of these quantities using NRLMSISE-00 has been included in InfraMAP calculations. This will improve fidelity of the modeling of thermospheric infrasound at little or no computational cost. Examples of typical ranges of these parameters over the annual cycle, as predicted from MSISE, are shown in Figures 14 and 15. The "spiky" features result from incorporation of the solar and geomagnetic measurements for the year 2001 (as shown in Figure 12).

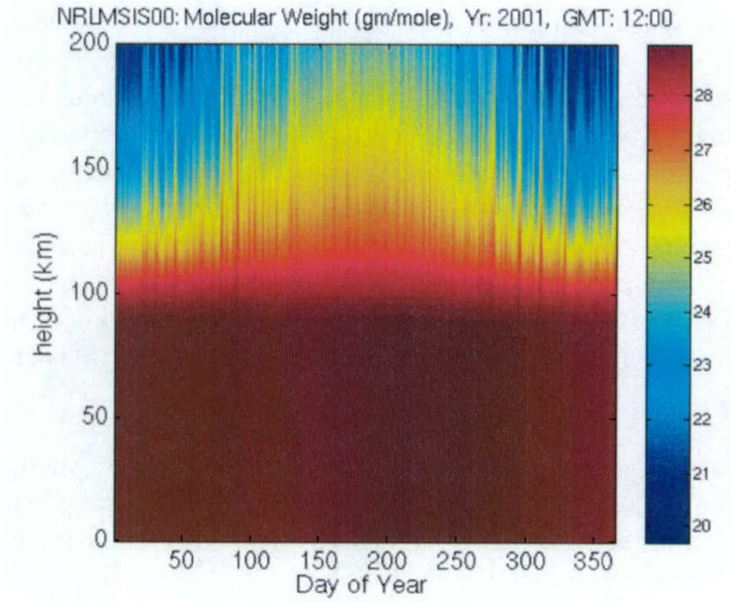

Figure 14. Modeled values of average molecular weight (in grams/mole) at a range of altitudes above the North Pole, calculated using NRLMSISE-00 over the annual cycle.

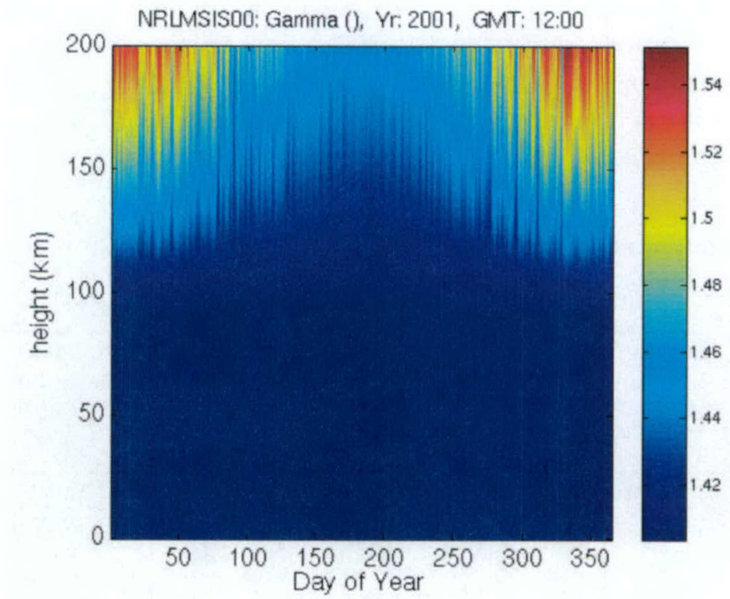

Figure 15. Modeled values of specific heat ratio (dimensionless) at a range of altitudes above the North Pole, calculated using NRLMSISE-00 over the annual cycle.

4.3 Applications to Special Events.

Comparison efforts are essential to build confidence in the modeling procedures and to identify areas where further refinements are required. Where ground truth is available, comparison results support event localization, phase identification and calibration efforts. The primary objectives of comparison studies are to assess improvements in predicting travel times and back-azimuths (for event location) and amplitudes and waveforms (for event identification). Several comparison studies have been performed during this effort using infrasonic sources of opportunity. Examples of these studies are presented here. Further details of the studies are available in the other referenced reports that have been produced under this contract, as listed in Section 4.4.

A recent ground truth event that demonstrates the value of the G2S atmospheric specification is the 18-Feb-2004 train car explosion in Neyshabur, Iran, which was observed at two IMS infrasound arrays, I31KZ (1579 km to the north) and I34MN (4078 km to the east). Effective sound speed profiles from the event location to I31KZ were shown earlier in Figures 9 and 10. At I31KZ, the explosion signal was observed to have travel times ranging from 5200 to 5835 sec. The observed azimuth deviation (from the great circle) was -7.9 deg. Ray-tracing calculations were made using both climatology and G2S, and results are presented in Table 1. Rays are classified as either stratospheric (S), thermospheric (T) or hybrid (S/T). The predicted travel times that are consistent with the observation are shown in bold, with those rows shaded. Note that a stratospheric duct (ray class S) is only identified using G2S. Furthermore, the predicted azimuth deviation is approximately 95% of the observed value using G2S, compared with less than 60% using HWM and MSIS. In this case, near-real-time specifications significantly improve both travel time and azimuth predictions compared to climatology. Depictions of propagation calculations using ray-tracing models are shown in Figures 16 and 17 and using PE models are shown in Figures 18 and 19.

Table 1. Propagation model results for 18-Feb-2004 train car explosion at Neyshabur, Iran, observed at I31KZ.

Atmospheric Specification	Ray Class	Travel Time	Delta Travel Time vs. 1st observation	Azimuth Deviation	Delta Azimuth Dev. vs. observ.
NRL-G2S	S/T	**5409**	209	-7.5	-0.4
	S	**5420**	220	-7.4	-0.5
	S/T	**5530**	330	-7.1	-0.8
	T	**5643**	443	-6.7	-1.2
	T	6032	832	-6.0	-1.9
	T	6515	1315	-5.2	-2.7
HWM/MSIS	T	**5718**	518	-4.5	-3.4
	T	6109	909	-4.5	-3.4
	T	6575	1375	-4.0	-3.9

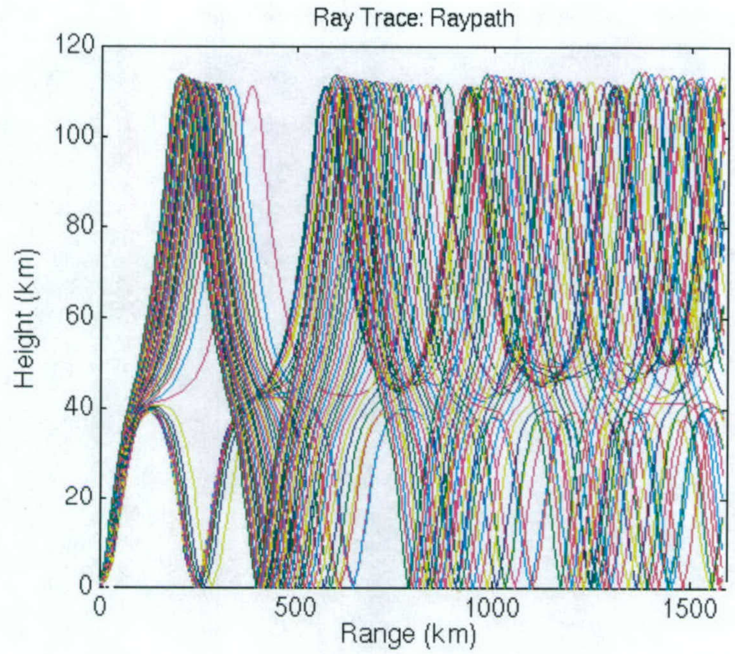

Figure 16. Range-dependent ray-tracing from Neyshabur, Iran to I31KZ, 18-Feb-2004, using G2S.

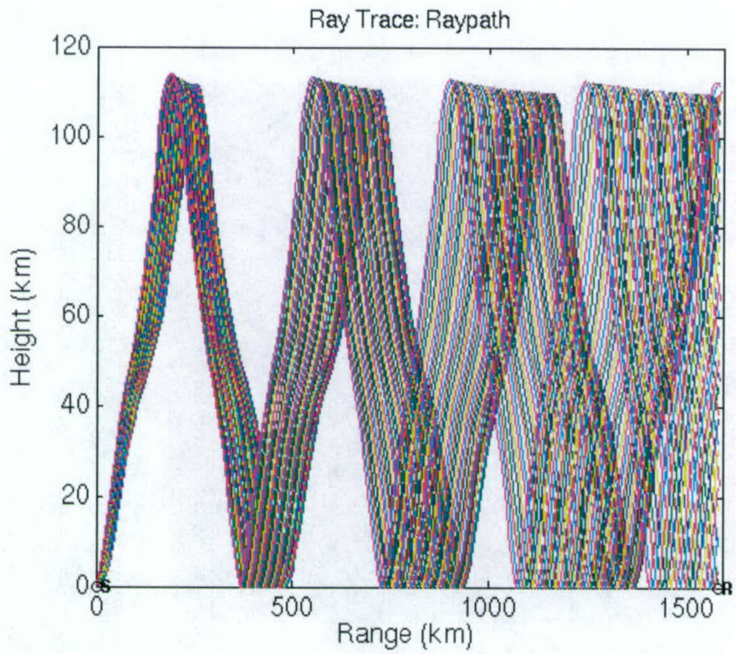

Figure 17. Range-dependent ray-tracing from Neyshabur, Iran to I31KZ, 18-Feb-2004, using climatology.

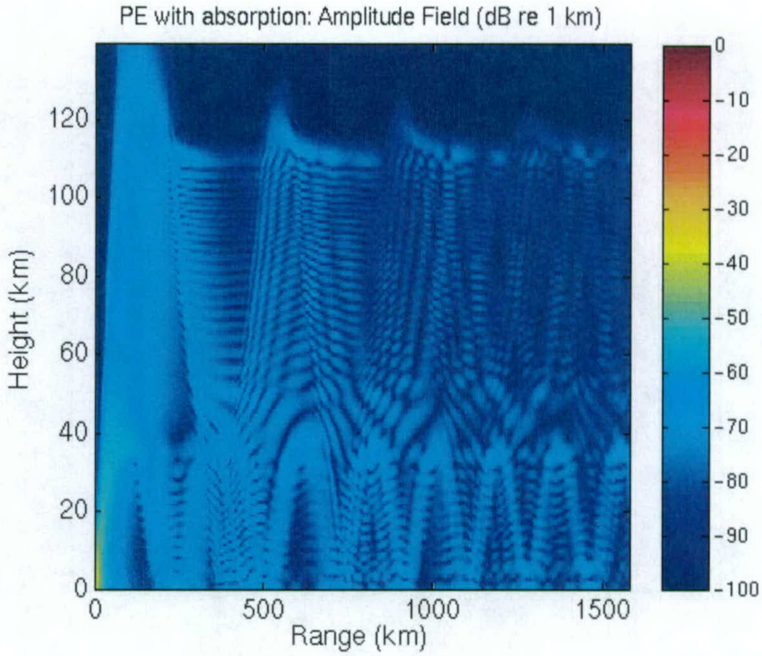

Figure 18. Parabolic equation amplitude field at 0.1 Hz from Neyshabur, Iran to I31KZ, 18-Feb-2004, using G2S.

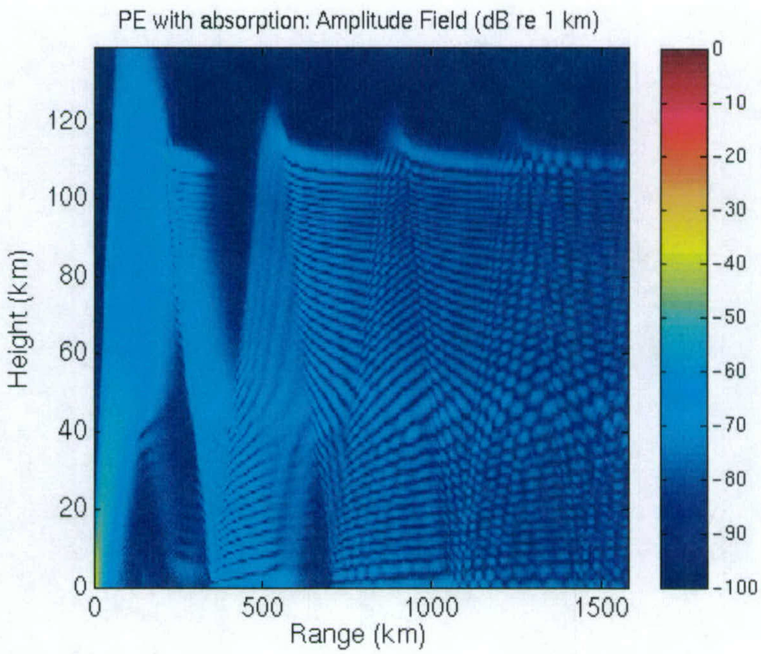

Figure 19. Parabolic equation amplitude field at 0.1 Hz from Neyshabur, Iran to I31KZ, 18-Feb-2004, using climatology.

Rocket launches may serve as useful ground truth data for infrasound [McLaughlin *et al.*, 2000] and also represent an excellent source of opportunity for model validation. Rocket and missile launches from the Eastern US were observed extensively in the 1960's and 1970's at Palisades, NY and elsewhere, and a series of reports describing them (for example, [Balachandran and Donn, 1971]) were issued by scientists at Lamont-Doherty Geological Observatory and the US Army Electronics Command. More recently, space shuttle launches have been observed at Los Alamos (DLIAR) and at Lac du Bonnet (I10CA), among other locations. Model predictions using InfraMAP have been compared to observations at Los Alamos, NM and Blossom Point, MD, as discussed in a previous contract report [Norris and Gibson, 2003].

Further model-to-data comparisons have been made in this effort. InfraMAP was used to determine eigenrays to DLIAR and I10CA from points along the space shuttle trajectory, with HWM-93 and MSISE-90 used for environmental characterization. Two continuously moving sources (the ascending orbiter and the descending solid rocket boosters) were modeled as a series of discrete sources separated in space and time. For each eigenray, an arrival azimuth and an arrival time (referenced to the launch time) were determined. Infrasound detections are determined from computations using MatSeis and Infratool [Young, *et. al.*, 2002]. Reasonably good agreement in both travel time and azimuth has been obtained between ray tracing model results using InfraMAP and observed infrasound, and biases have been quantified for individual events [Gibson and Norris, 2002b; Gibson and Norris, 2002c]. Components of infrasound signals have been associated with both the ascending orbiter and the descending solid rocket boosters. More recently, analyses have been conducted of annual trends in observability, travel time and azimuth of infrasound signals from space shuttle launches [Gibson and Norris, 2002d; Gibson and Norris, 2003c].

Analyses were made of 22 space shuttle launches between October 1998 and January 2003. Of these 22 launches, infrasound data were available corresponding to 18 launches at DLIAR and I10CA. Based on preliminary analysis using DLIAR data, two launch events were clearly observed (in calendar months May and July) and two were weakly observed (in calendar months May and June). Based on preliminary analysis using I10CA data, eight launch events were clearly observed (in calendar months February through August) and five were weakly observed (in calendar months February through November).

Infrasound detections, determined from computations using MatSeis and Infratool, are shown in Figures 20 and 21 for the observation at I10CA of one launch event (shuttle mission STS-96) on 27-May-1999. (Infratool parameters included a bandwidth of 0.3 to 3.0 Hz, and 400 F-k bins.) Figure 20 shows azimuth versus arrival time (referenced to launch time), and Figure 21 shows trace velocity versus arrival time (referenced to launch time). Clear detections can be seen over duration of nearly 1000 seconds. A detailed view of the azimuth versus arrival time is shown in Figure 22. Eigenray predictions were made using trajectories of both orbiter and solid rocket boosters, and model results are shown in Figure 23. Stratospheric rays and thermospheric rays are depicted separately for both the orbiter and the solid rocket boosters. The primary observed arrival (see Figure 22) is reasonably well modeled by the stratospheric rays from the orbiter (circles) and boosters (squares), shown in Figure 23.

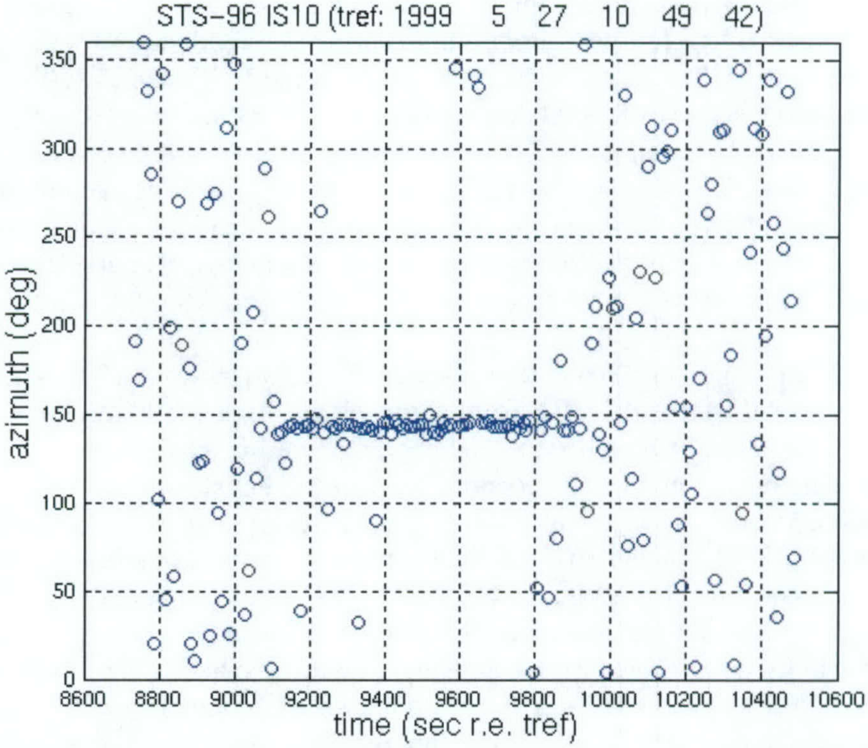

Figure 20. Azimuth of infrasound detection of space shuttle launch at I10CA.

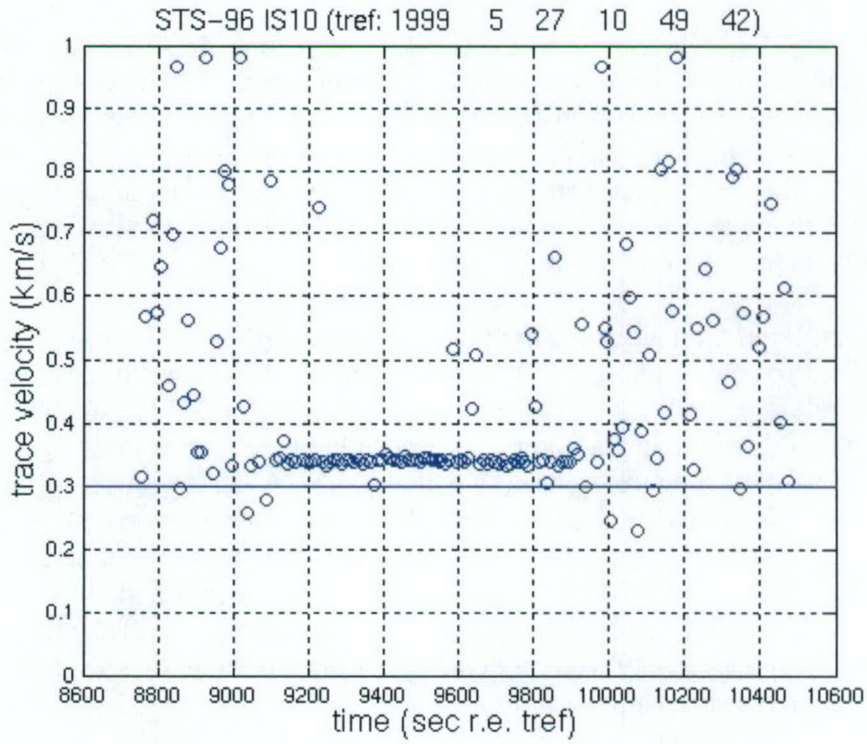

Figure 21. Trace velocity of infrasound detection of space shuttle launch at I10CA.

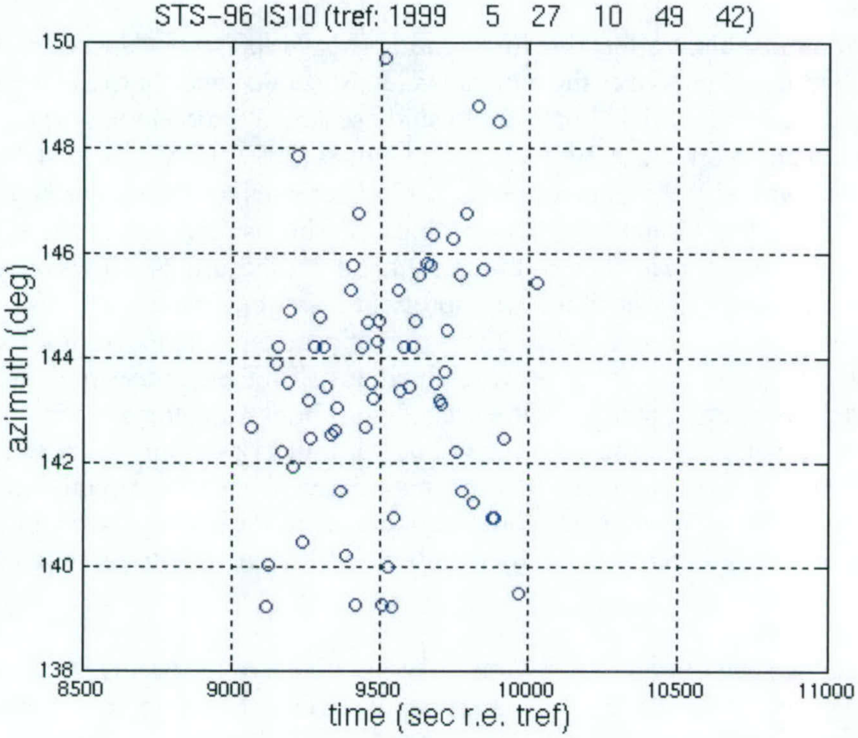

Figure 22. Detail of azimuth of infrasound detection of space shuttle launch at I10CA.

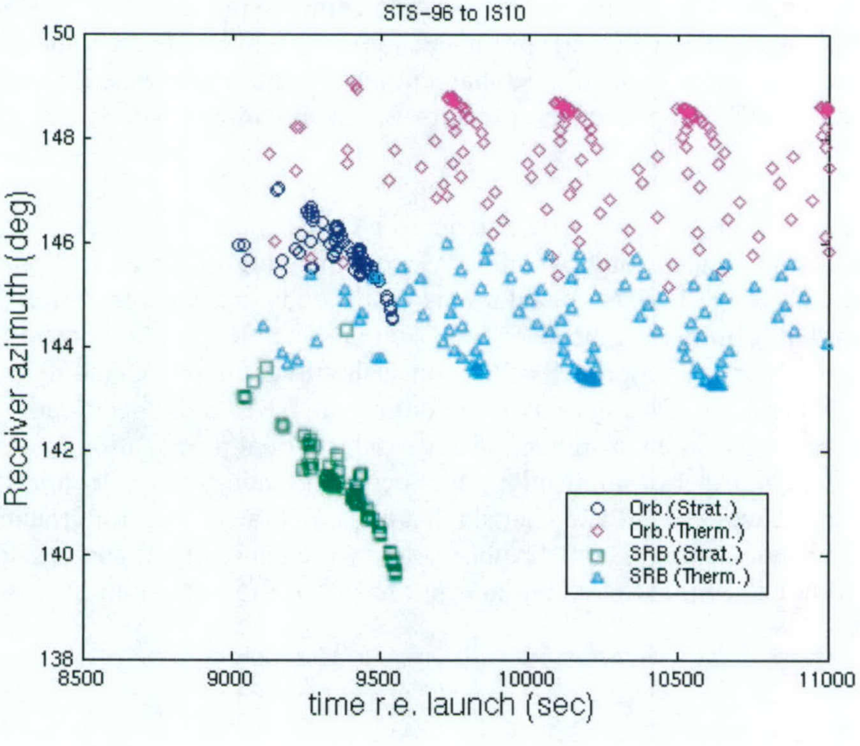

Figure 23. Predicted azimuth of infrasound at I10CA from space shuttle launch, based on eigenrays determined using trajectories of orbiter and solid rocket boosters.

The importance of atmospheric effects on infrasound propagation can be shown by considering propagation from similar events over the annual cycle. Several space shuttle launches observed at I10CA were analyzed and modeled in order to study seasonal trends in long range infrasound propagation [Gibson and Norris, 2002d; Gibson and Norris, 2003c]. All the shuttle launches in this study followed nominally the same trajectory. Comparisons between infrasound propagation model predictions using HWM and MSIS climatology and infrasound observations at I10CA, as a function of day-of-year, are presented in Figures 24 and 25. Figure 24 shows annual variability in travel time, and Figure 25 shows annual variability in azimuth. Instead of showing each eigenray prediction separately, as in Figure 23, the set of predicted eigenrays for each launch event is represented by a bar, the length of which includes all the eigenray predictions. Blue bars indicate predicted propagation paths from the ascending orbiter trajectory; green bars indicate predicted propagation paths from the descending booster trajectory. Only stratospheric eigenrays are considered in this aspect of the study; thermospheric rays are not represented in the figures. Instead of showing each infrasound detection separately, as in Figure 22, the set of detections for each observed launch event is represented by a hollow red bar, the length of which includes all the detections.

Seasonal trends can be seen in both travel time and azimuth. Stratospheric arrivals are not predicted for the December (day 335 to day 365) launch events that were considered in this study; furthermore, these events were not observed at I10CA. Observed arrival time trends and azimuth trends are generally well predicted by the stratospheric eigenrays, although not all details are well predicted using this technique. Referring to Figure 25, observed infrasound appears to be consistent with stratospheric propagation components from both the orbiter and the solid rocket boosters, particularly during spring and summer months. Further modeling of the launch events using an updated atmospheric characterization, in order to see if travel time and azimuth predictions could be improved over results using climatology, would be of interest in this study.

During this contract effort BBN also participated in the Department of Defense Columbia Investigation Support Team Infrasound Working Group, the work of which was presented in the report edited by Bass [2003]. BBN's contributions to the study are documented in detail in several appendices that form part of the Working Group report. InfraMAP was used to model infrasound from the reentry and approach of the space shuttle Columbia (STS-107) up to the point of its untimely breakup. During this investigation, the NRL-G2S specifications were used to characterize the propagation environment. Range-independent propagation modeling was conducted from a large number of points along the reentry trajectory to the locations of those infrasound arrays in the western US and Canada that observed the event. Ray tracing model predictions of arrival time, azimuth and elevation angle were generally in good agreement with the observations, although modeling did not account for all of the signal complexity at the more distant stations.

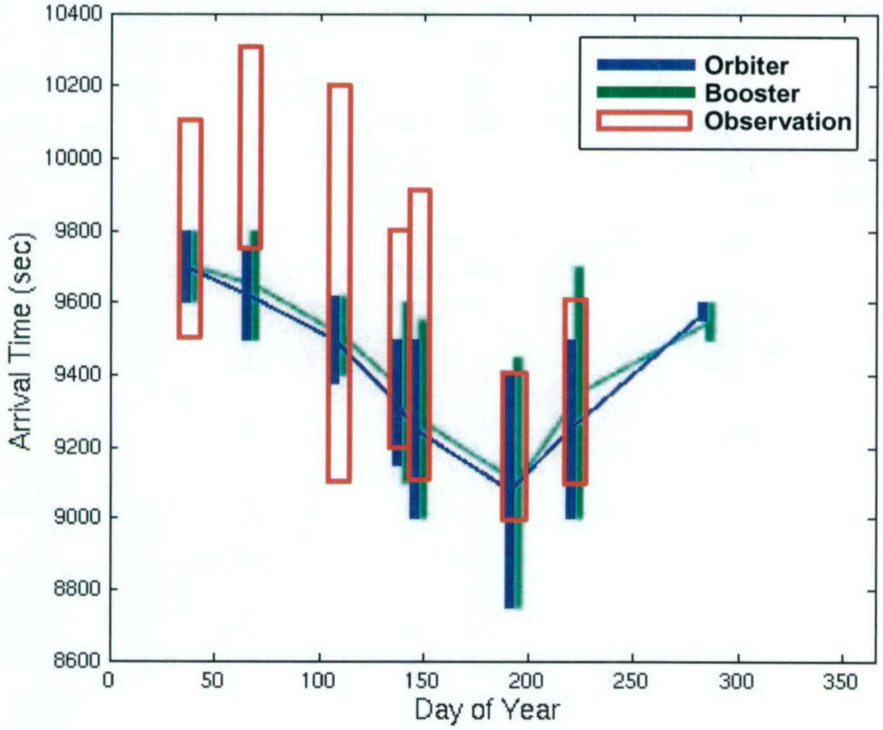

Figure 24. Model-to-data comparison of arrival time at I10CA for shuttle launches.

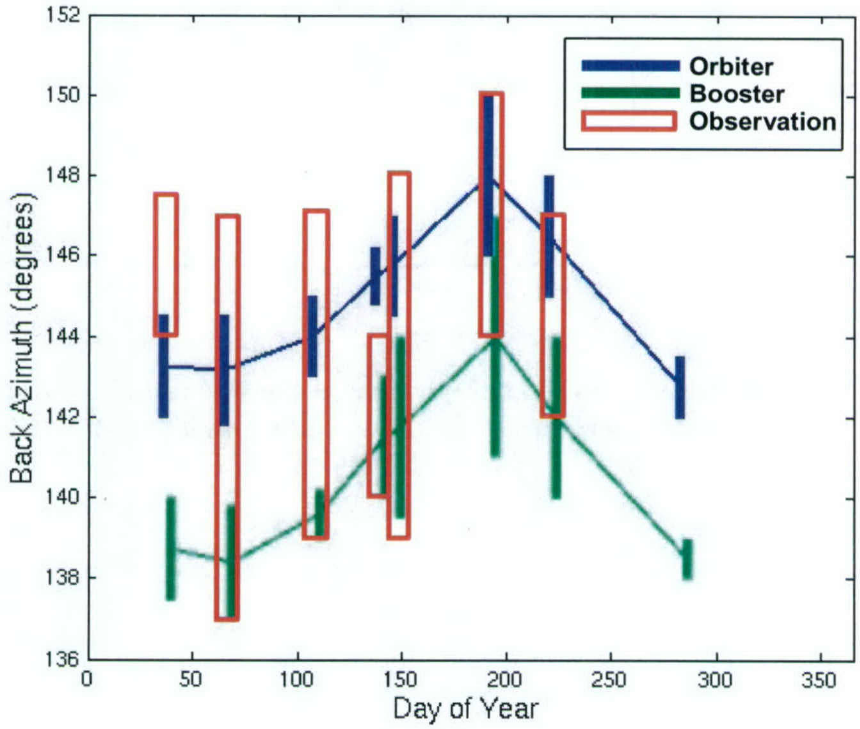

Figure 25. Model-to-data comparison of azimuth at I10CA for shuttle launches.

One example result from the Columbia reentry study is presented here to illustrate the model fidelity. Figure 26 shows a comparison of ray-tracing results with detections at Pinon Flat, CA (I57US) as computed using MatSeis and Infratool. (The analysis passband is 1-8 Hz.) Predicted infrasound arrivals at I57US using ray-tracing (circles, diamonds and squares) are compared to observations (triangles) from the reentry of Columbia (STS-107). The vertical axis shows azimuth (in degrees) and the horizontal axis shows arrival time (in UT). The color bar indicates the longitude of the orbiter at the origin time of each modeled ray arrival. The observed trends in azimuth and travel time from the moving source are generally well predicted. The results can be used to determine what portion of the reentry trajectory contributed to infrasound signals received at a given time of interest.

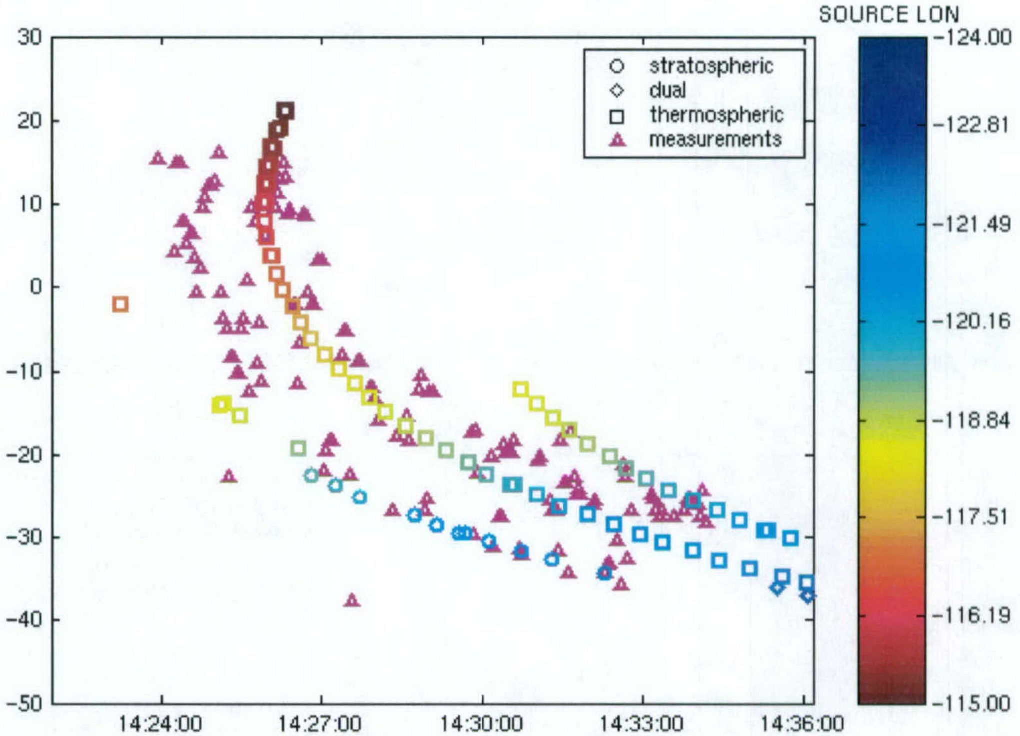

Figure 26. Comparisons between predicted infrasound arrivals at I57US using NRL-G2S (circles, diamonds and squares) and observations (triangles) from the reentry of Columbia (STS-107).

4.4 Reports to the Research Community.

Under this contract, BBN participated in the 24th Seismic Research Review [Norris and Gibson, 2002b], the 25th Seismic Research Review [Gibson and Norris, 2003a] and the 26th Seismic Research Review [Gibson and Norris, 2004]. The participation included submission of papers for the proceedings, presentation of posters, and attendance at meeting activities.

BBN also has given technical reports in several other meetings. We presented work performed under this contract at the Infrasound Technology Workshop in Kauila-Kona, HI [Gibson and Norris, 2001], at the Infrasound Technology Workshop in De Bilt, Netherlands [Gibson and Norris, 2002c] and at the Infrasound Technology Workshop in La Jolla, CA [Gibson and Norris, 2003b]. Work on infrasound from rockets was given during a special session on infrasound at the Acoustical Society of America meeting in Cancun [Gibson and Norris, 2002d] and during a special session on infrasound at the 2003 Fall Meeting of the American Geophysical Union (AGU) [Gibson and Norris, 2003c]. Progress updates were also presented at annual AFRL/NNSA/SMDC Infrasound Research Program Reviews in 2002 and 2003.

BBN's contributions to the Department of Defense Columbia Investigation Support Team Infrasound Working Group are documented in detail in four appendices that form part of the Working Group report [ed. Bass, 2003]. BBN's detailed analyses are presented in the appendix entitled "Preliminary Infrasound Propagation Modeling Analysis of Space Shuttle Columbia (STS-107) Reentry" and in three subsequent addenda to the original analysis, all authored by R. Gibson and D. Norris.

Section 5
Conclusions and Recommendations

New capabilities have been developed for InfraMAP, a user-friendly software tool kit to predict the critical propagation characteristics that affect localization and detection performance of an infrasound monitoring network. The new capabilities enable incorporation of two types of near-real-time atmospheric characterization. The software incorporates a common user interface for:

- Accessing atmospheric characterizations, e.g., temperature and wind profiles.
- Exercising infrasound propagation models.
- Integrating the propagation models with the atmospheric environment.
- Viewing output data.

Specific features of the software that represent improvements over existing infrasound modeling capabilities include:

- Integration of range-dependent, near-real-time sound speed and winds with propagation models.
- The ability to account for actual time and date rather than seasonal or monthly averages.

The ability to model infrasound propagation and assess source location is therefore enhanced. Further investigations of environmental variability and its effect on propagation should be conducted. Additional development of network performance models incorporating these variability effects, as well as noise effects, should also be performed.

The InfraMAP tool kit is used to predict the critical propagation characteristics that affect infrasound localization and detection. Adequate atmospheric characterization is necessary to correct for biases in travel time and azimuth that result from the propagation environment in order avoid phase misidentification or large location errors. *In situ* observations of winds and temperature can be used in InfraMAP for range-independent propagation modeling. New enhancements provide and utilize linkages between infrasound propagation models and sources of measured and modeled atmospheric updates. Atmospheric characterizations include:

- the Navy's NOGAPS synoptic model of the atmosphere;
- the NRL-G2S global atmospheric specification;
- the updated NRLMSISE-00 climatology;
- archived observations of geomagnetic activity and solar flux.

Techniques have been developed to integrate output from the NOGAPS numerical weather prediction model with climatology for use in range-dependent propagation models. The NRL-G2S atmospheric specifications can also be used with range-dependent models. InfraMAP's integrated set of models will allow for higher fidelity propagation modeling than has previously been available to the infrasound monitoring community.

Other high-fidelity environmental characterizations should be considered for integration into an enhanced version of the InfraMAP software, particularly mesoscale models for use in studying short-range events of interest. As higher fidelity characterizations become available, they should be integrated into a next-generation version of the software. Efforts should also be made to evaluate resulting improvements over the baseline environmental models.

Model output has been compared to measured infrasound data corresponding to historical events. Rocket events, chemical explosions and bolides generate infrasound signals for use in model validation studies. Agreement is generally good for a number of cases investigated; however, certain cases are not well modeled using the mean atmospheric characterizations. Further modeling of a large set of observed ground truth events, using updated atmospheric characterizations, should continue in order to quantify the improvements in travel time and azimuth predictions that are achievable. These investigations should focus on first establishing a baseline and then documenting the modeling improvements achievable with near-real-time updates as compared to climatology. The results may also be useful for identifying improvements that could be made to the atmospheric specifications.

Sensitivity investigations should continue in order to identify specific areas where additional infrasound research and further development of modeling capabilities are needed.

Efforts should continue on the development of time-domain propagation modeling techniques, including the consideration of non-linear effects. Although ray-tracing is a powerful technique for predicting travel time and azimuth deviation, it is not always sufficient for predicting the detailed features of infrasound observations from ground truth events. The integration of time-domain models with near-real-time atmospheric characterizations should be undertaken in order to conduct model comparison studies and to model infrasound propagation from observed events.

Section 6
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Appendix
Abbreviations and Acronyms

AFRL	Air Force Research Laboratory
AFTAC	Air Force Technical Applications Center
AGU	American Geophysical Union
A_P	planetary equivalent disturbance amplitude
DTRA	Defense Threat Reduction Agency
FNMOC	Fleet Numerical Meteorology and Oceanography Command
GUI	Graphical User Interface
G2S	Ground to Space
HARPA	Hamiltonian Ray-Tracing Program for Acoustic Waves in the Atmosphere
HWM	Horizontal Wind Model
IMS	International Monitoring System
InfraMAP	Infrasonic Modeling of Atmospheric Propagation
LANL	Los Alamos National Laboratory
MSIS or MSISE	Extended Mass Spectrometer – Incoherent Scatter Radar model
NASA	National Aeronautics and Space Administration
NGDC	National Geophysical Data Center
NNSA	National Nuclear Security Administration
NOAA	National Oceanographic and Atmospheric Administration
NOGAPS	Naval Operational Global Atmospheric Prediction System
NRL	Naval Research Laboratory
NRL-G2S	Naval Research Laboratory – Ground to Space specification
NRLMSISE	Naval Research Laboratory Extended Mass Spectrometer – Incoherent Scatter Radar model
PE	Parabolic Equation
SMDC	Space and Missile Defense Command
UT	Universal Time
WKB	Wentzel-Kramer-Brillouin method

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